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Wildfire Updrafts and Downdrafts Effects of Aerial Vehicles Flight Mechanics

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Abstract

The intense heat of wildfires causes strong updrafts and corresponding downdrafts around fires as the air heats and cools through convection. Airborne cloud radar observations of intense megafires have found updrafts of up to 130.4 mph and downdrafts of 65.5 mph, which are comparable conditions found in supercell thunderstorms. These extreme conditions can lead to suboptimal flight performance of firefighter aircraft as the aircraft are jarred and buffeted by sudden turbulent winds. An analysis to characterize the effects of the wind forces on aircraft wings of various platforms, under updraft and downdraft loads, is conducted utilizing finite element analysis. Specifically, the wings of the King Air 350, C-130 and Boeing 747-400 were chosen to represent varying small, medium, and large aircraft respectively. The wings are modeled in Patran and Nastran, which are purpose built for finite element analysis. Data on wing stress and displacement were generated and compared to known yield strength of Aluminum 6061-T6. Preliminary analysis was conducted with the assumption that air pressure was constant between heated and ambient air and that airflow was perpendicular to the wings. It was found that the updrafts caused a pressure of 27.189 lbf/ft2 and the downdrafts exerted a pressure of 7.428 lbf/ft2. It was also found that spar stresses exceeded that of the yield strength of the material in the middle spar of the King Air 350 and the rear spar of the Boeing 747-400 resulting in the bars yielding. Such yielding could potentially lead to a weakening of wing structural integrity.

Nomenclature

a = speed of sound, m/s

C_d = coefficient of drag

D = drag force, lbf

γ = ratio of specific heats

g_0 = gravitational acceleration, m/s^2

h = height of pressure calculation, m

h_b = reference height, m

L_b = temperature lapse rate, K/m

M = Mach number

M = molar mass of Earth’s air, kg/mol

P = pressure, Pa or lbf/ft^2

P_b = reference pressure, Pa

R = specific gas constant of air, J/(K kg)

R^* = universal gas constant, J/(mol K)

ρ = density, kg/m^3

S = wing area, ft^2

T = temperature, K

T_b = reference temperature, K

V = velocity, m/s

Introduction

Updrafts and Downdrafts

When a wildfire burns it produces heat energy, which is transferred to the surrounding air through convection. As the air heats up it becomes less dense, leading to it rising in the atmosphere, this process is what produces updrafts (Werth 2011, 77-78). As the air goes upwards it releases some of its energy to the surrounding air primarily through convection, which causes the air to cool down, increase in density and sinking (Werth 2011, 77-78). When the air from the updraft rises rapidly it leaves a void, which cooler (relative to the updraft) air moves into and the process begins anew, this air rushing downwards after rising and cooling or to fill in the void from rising air are both downdrafts. Updrafts are found primarily in the center of super-heated air plumes while the downdrafts occur on the outer edges and sides of such plumes. The hotter the air the faster the updrafts can become and consequently the faster the downdrafts will be (Werth 2011, 77-78). Megafires and wildfires can heat the air to such extremes that their updrafts and downdrafts can greatly affect aircraft flying through them as the vehicle are suddenly battered by hot high-speed air from either above or below. Such conditions can lead to sudden strains and stresses being developed on the wing, which can be safe if rarely occurring but for aircraft exposed to such conditions often, such as firefighting aircraft, then these forces may result in the need for increased maintenance to stay vigilant of these sudden forceful loads. Unfortunately, such extreme updrafts and downdrafts are not extremely well documented as they occur only above extreme fires where planes will often be diverted away from anyways, leading to a lack of encounters.

One recent civil incident occurred in 2020, a Qantas Boeing 737 flight from Melbourne to Canberra, Australia flew into a far more minor updraft above a major bush fire which still violently shook the entire craft forcing it to make an emergency landing (Black and Jordan 2020). The passenger aircraft was set suddenly into severe turbulence while only passing on the very edge of a major hot air plume. The aircraft was able to land safely after soon after and with no major damage found (Black and Jordan 2020). In another example researches attempting to study strength of such updrafts specifically had an incident where, when flying into one the aircraft was buffeted so violently that a researcher was injured and the flight had to be recalled (Rodriguez, Lareau, Kingsmill, and Clements 2020). The details of this research are discussed further in the Source Data section.

Aircraft Platforms Under Study

Three aircraft's wings are under study, the King Air 350, C-130, and Boeing 747-400. These three aircraft were selected as to represent small, medium, and large aircraft. They were also selected as all three are used in firefighting applications, which would have the highest likelihood of encounter such severe updrafts and downdrafts. All aircraft can be seen in Figure 1 with general data for all aircraft found in Table 1.

Figure 1. All aircraft under study. (a) University of Wyoming's King Air 350 used for meteorological testing. (b) Converted C-130 using a MAAFs firefighting system. (c) Global Supertanker Service's Boeing 747-400 firefighting air tanker.

Table 1. Aircraft characteristics for planes under study

Aircraft	**Wing Area [ft^2]**	**Root Chord Length**	**Skin Thickness [in]**	**MTOW [lb]**	**Airfoil Used**
King Air 350	310	7.286	0.04	16,500	NACA 23018
C-130	1745	15.168	0.16	175,000	NACA643418-il
Boeing 747-400	5963	47.51	0.075	910,000	BACXXX

The King Air 350 is a small twin turboprop aircraft used in a variety of roles from private passenger plane, to short distance cargo aircraft, to a research platform. Notably for this analysis it is the aircraft used by the University of Wyoming to record the data sets that form the basis of this paper. It has a straight rectangular wing in which its turbo prop engines are mounted. Past the halfway point of the wing, the wing tapers forward.

The C-130 is a medium range dedicated cargo aircraft for the United States Air Force. Using four turboprop engines and a unique rectangular wing with forward taper, allows it to land and takeoff on short unprepared runways for military logistics. Its wing is far more squared off and rectangular than the King Air 350's. Later variants of this aircraft have been pressed into civil service as medium firefighting aircraft as either a dedicated tanker or non-permanent conversion using the MAAFs tank system.

The Boeing 747-400 is a large wide body jet originally developed in the 1970s. It is uses four large turbofan engines and large swept back wings allowing it a high degree of speed for its size, unlike the other aircraft understudy has an equilateral taper along its length from root to tip. It has primarily been used in the civilian sector as either a long-haul passenger or cargo aircraft. Over the years it is also seen itself in more unique roles as a supertanker firefighting aircraft.

Source Data

Research was compiled to find instances of extreme updrafts and downdrafts to use as a metric for worst case scenario events. Dr. Rodriguez and their researchers studied the extreme conditions above megafire Pioneer in 2016 to attempt to understand how strong wildfire updrafts could become when produced by a megafire (Rodriguez, Lareau, Kingsmill, and Clements 2020). In this line of study, they recorded record breaking speeds for the meteorological community. They worked with the University of Wyoming's King Air 350 team to study the thermodynamic structure and velocity of air above the Pioneer wildfire during 2016 in Idaho. Data from their paper can be found in Table 2. During one of their flights the University of Wyoming's King Air 350's flew into a strong enough updraft such that a researcher was injured, and the flight had to canceled, which illustrates how strong these updrafts and downdrafts can be and the effects it can have on the aircraft and its occupants (Rodriguez, Lareau, Kingsmill, and Clements 2020).

Table 2. Source data (Rodriguez, Lareau, Kingsmill, and Clements 2020).

Condition	Velocity [m/s]	Temperature [K]	Altitude [m]
Updraft	58.3	323.1	4800
Downdraft	29.3	319	4200

It was noted in their report that updrafts and downdrafts of this scale were a previously undocumented hazard to aircraft operating in the area of such megafires.

Methodology

This analysis conducts study of stress on aircraft wing spars when such wings are under the effects of severe updrafts and downdrafts. This is accomplished through preliminary analysis on wind conditions for such events and then develop finite element analysis models in Patran and Nastran to study how aircraft wings will react to such loads (Hexagon MSC Software 2021). First, data was retrieved on real life examples of extreme updrafts and downdrafts to use as a basis of greater analysis (Rodriguez, Lareau, Kingsmill, and Clements 2020). From there, this data was used to derive the ambient environment around the updrafts and downdrafts such that density of the heated air could be calculated. Next, density data are combined with velocity data and the assumption that the updrafts and downdrafts will contact wings from directly above or below resulting in the wings acting like a flat plate to calculate the drag per unit area or pressure exerted by such conditions on aircraft. Following this total drag forces on all three aircraft under study is calculated.

Geometric models were then developed in Solid Edge based on aircraft wing geometry to confirm aircraft dimensions before being recreated in Patran. From here the wings are created and meshed to allow for loads to be applied to the wings allowing for finite element analysis to be conducted. Data of these loads on the wings and their geometry is then fed into Nastran and its results are fed back into Patran for analysis. The resulting stresses are then recorded and compared to existing material properties.

Preliminary Analysis

Derivation of Pressures and Forces

First, ambient values needed to be calculated at altitude for updraft and downdraft to later calculate density. This was accomplished by using the Barometric formula at each altitude as shown in Eq. (1) with results of the calculations displayed in Table 3.

$$P = P_b \cdot \left[\frac{T_b + L_b \cdot (h - h_b)}{T_b} \right]^{\frac{-g_0 \cdot M}{R^* \cdot L_b}}$$

$$= 101325 Pa \cdot \left[\frac{288.15K + \left(-0.0065 \frac{K}{m} \right) \cdot (4800m - 0m)}{288.15K} \right]^{\frac{-9.81 \frac{m}{s^2} \bullet 0.028944 \frac{kg}{mol}}{8.3145 \frac{J}{mol \cdot K} \cdot \left(-0.0065 \frac{K}{m} \right)}} \tag{1}$$

$$= 55,503.49 Pa$$

Table 3. Ambient Pressures at Altitude of Updraft and Downdraft

Condition	**Altitude [m]**	**Pressure [Pa]**
Updraft	4800	55,503
Down Draft	4200	60,073

Before calculating density, it first must be found if the air is traveling slow enough to be incompressible as if so, it will greatly reduce required calculations. The calculations of speed of sound and Mach number are shown in Eq. (2) and Eq. (3) respectively, with the table of resulting values displayed in Table 4.

$$a = \sqrt{\gamma RT} = \sqrt{1.4 \cdot 287.04 \frac{J}{K \cdot kg} \cdot 323.1K} = 360.33 \frac{m}{s} \tag{2}$$

$$M = \frac{V}{a} = \frac{58.3 \frac{m}{s}}{360.33 \frac{m}{s}} = 0.162 \tag{3}$$

Table 4. Updraft and downdraft Mach numbers

Condition	**Velocity [m/s]**	**Speed of Sound [m/s]**	**Mach Number**
Updraft	58.3	360.33	0.162
Downdraft	29.3	358.04	0.082

Based on the above calculations, both condition's Mach numbers are under 0.3 which means that it can be assumed that the air is incompressible, meaning in this case that velocity has a minimal effect on the density of the air. It can also be assumed that the ambient air's pressure is the same pressure applied by the super-heated air. With this assumption in mind, density can now be calculated using Eq. (4) with the resulting densities shown in Table 5.

$$P = \rho RT \Rightarrow \rho = \frac{P}{RT} = \frac{55,503.49\,Pa}{287.04\,\frac{J}{K \cdot kg} \cdot 323.1K} = 0.5985\,\frac{kg}{m^3} \tag{4}$$

Table 5. Density of heated air of updraft and downdraft

Condition	**Density [kg/m^3]**
Updraft	0.5985
Downdraft	0.6561

Finally, the drag per unit area can be calculated, which will be used to develop the pressure exerted onto the wings in later modeling. It was assumed that updrafts and downdraft would come directly perpendicular to the wing as to act as a worse case stress scenario as this will lead to maximum stress. This means that for the drag calculations the wing can be approximated as flat plates perpendicular to the air flow which gives them a coefficient of drag of 1.28 (NASA). The equation for this calculation is shown in Eq. 5 and its data is displayed in

Table 6. Note that units have switched to imperial as to better interface with known wing geometry later on in this analysis.

$$\frac{D}{S} = \frac{1}{2} C_d \rho V^2 = \frac{1}{2} \cdot 1.28 \cdot 0.5985 \frac{kg}{m^3} \left(58.3 \frac{m}{s^2} \right)^2 = 1,301.84 Pa = 27.19 \frac{lbf}{ft^2} \tag{5}$$

Table 6. Drag per unit area for updraft and downdraft

Condition	**Drag per unit Area [lbf/ft^2]**
Updraft	27.189
Downdraft	7.528

Next to give a sense of scale of what these pressures represent the drag for each aircraft was calculated using values of wing area from Table 1, shown in Eq. (6) with the results of force from each condition shown in Table 7.

$$D = \frac{D}{S} \cdot S = 27.19 \frac{lbf}{ft^2} \cdot 310\, ft^2 \tag{6}$$

Table 7 Forces from updrafts and downdrafts on various aircraft

Aircraft	**Updraft Force [lbf]**	**Downdraft Force [lbf]**
King Air 350	8,428.93	2,333.82
C-130	47,445.63	13,137.14
Boeing 747-400	162,130.82	44,892.14

These forces are unsurprisingly massive and can explain why the researchers had to call off their flight when one researcher was injured due to the forces of the updraft violently hitting their King Air 350 (Rodriguez, Lareau, Kingsmill, and Clements 2020). These forces alone present a risk to the aircraft, but analysis will go further to understand how they affect the planes structurally. It must also be noted that these forces are most likely applied for only a short time as the plane will reorient itself to go with this new sudden flow which can also throw off the aircraft's flight path and potentially lead to other problems.

Geometry and Simulation

Aircraft Wing Geometries

Aircraft wing geometries were first sketched in Solid Edge to get exact point locations for nodal creation later. No exact sketches existed of the wings so information that could be found such as wing root length was compiled and compared to PDFs sketches of the aircraft, from which a sizing factor was applied to measurements taken on such PDFs to create the dimensions of the wings. The exact dimension of the wings used in this analysis are found in Figure 2 for the King Air 350, C-130, and Boeing 747-400.

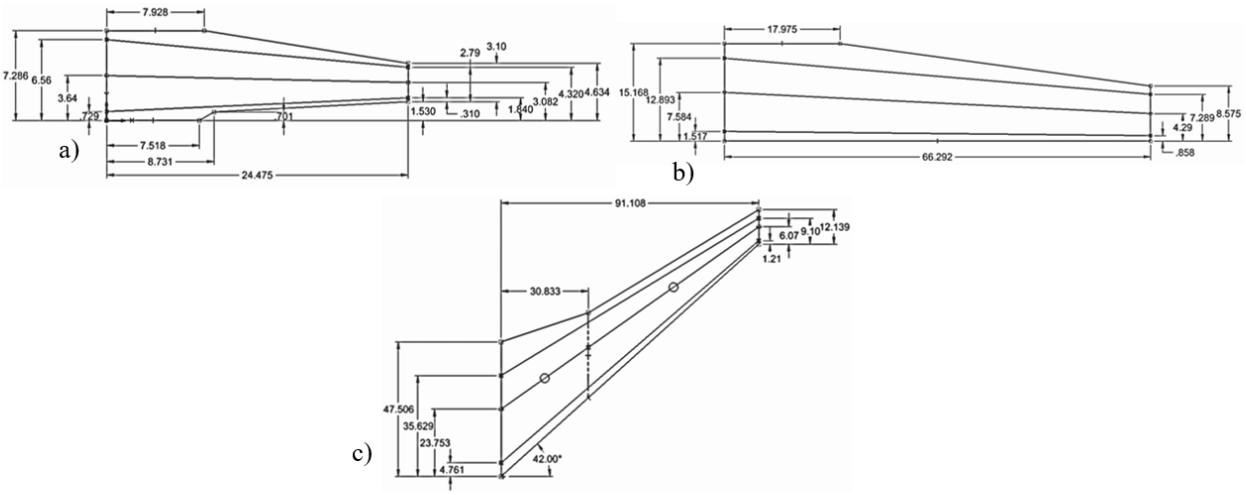

Figure 2. Wing dimension for all aircraft under study in feet a) King Air 350 Wing Dimensions [ft] b) King C-130 Wing Dimensions [ft] c) Boeing 747-400 Wing Dimensions [ft].

Next spar dimensions were attempted to be found. Unfortunately, such dimensions for sizing are proprietary and not available to the public. Instead, an idealized beam was created, which would be scaled up and down based on the thickness of the wing at the point where the spar is created. This idealized beam's dimensions are shown in Figure 3.

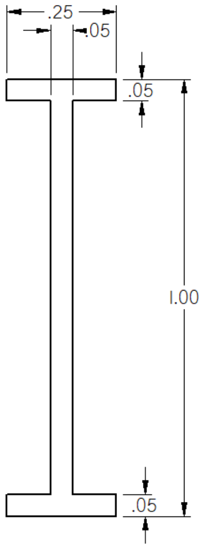

Figure 3. Dimensionless Idealized Beam.

Due to this idealized beam being used, it meant that all aircraft spars would simply be scaled up and down versions of each other. When scaling this beam its aspect ratio is locked, such that it will always maintain this ratio of flanges size and thickness to beam height. Height of each beam is based on the thickness of the root airfoil at the chord point where the ribs begin. All dimensions of the idealized beam are then multiplied by the thickness of the wing at that point. Dimensions of points for each airfoil were obtained from Airfoil Tools using the airfoils shown in Table 1 (Airfoil Tools). The dimensions and locations that each spar was placed and the height the idealized beam should be scaled to are shown in Table 8. The locations were generally set to be at 10% chord, 50% chord and as far back as could be possible without the spar going off the wing, which results in variation of the location of the rear spar.

Table 8. Wing spar location and thickness on aircraft

Aircraft	**Spar**	**Location/ percent of chord length**	**Beam Height [ft]**
King Air 350	Front	10%	1.024
	Middle	50%	1.155

	Rear	90%	0.315
C-130	Front	10%	1.756
	Middle	50%	2.461
	Rear	85%	0.591
Boeing 747-400	Front	10%	3.682
	Middle	50%	5.002
	Rear	75%	3.173

Spars, in reality, should become smaller as the wing goes on as the wing itself gets smaller towards the wing tips. This analysis however modeled the spars as being of a constant thickness based on the root airfoil's thickness. This decision was made as to simplify the geometry, analysis, and to try to overestimate the strength of the beams, as if they had problems at this size, they would definitely have them when smaller. It is also notable that in the real world additional structural components such as ribs exist and act to increase the strength of wings and would change the results of this analysis if included. Notably also the beams should actually be slightly shorter as in their current sizing they will stick out of the wing's 3-D geometry. These sizes were kept as to standardize spar sizing methods and allow the spars to be straight I beams.

Simulation Environment

Next, all wings were recreated in Patran, using dimensions shown in Figure 2. The geometry was generated by creating several point nodes to define the geometry. These were connected through curves, which themselves were then combined to form a surface for the leading edge, area between front and middle spar, area between middle and rear spar, and trailing edge areas. The original curves used to create the surfaces were retained to be used in the creation of the 1-D beam elements that would represent the spars. These surfaces represent the skin of the wing which is what the pressure of the updraft and downdraft will apply to and transfer load to the beam. The curves between surfaces will be turned into 1-D beams to represent the spars.

The material of the model was then defined, in this Aluminum 6061-T6 was selected and was applied to all parts of the wing, both the skin and the spars. The properties of this metal are shown in Table 9 (Aerospace Specification Metals Inc).

Table 9. Aluminum 6061-T6 Properties (Aerospace Specification Metals Inc)

Modulus of Elasticity	1,440,000,000 lbf/ft^2
Poisson’s Ratio	0.33
Tensile Yield Stress	5,760,000 lbf/ft^2
Fatigue Strength	2,016,000 lbf/ft^2

Meshes were then applied to these geometries. The meshes for each wing used similar mesh creation methods. The leading-edge skin and skin between spars were made using IsoMesh with quad elements and Quad4 topology. The trailing edge meshes were made using a Paver mesh with quad elements and Quad4 topology. Every spar mesh was created the same way, by creating 1-D elements from curves placed along their length using a bar2 topology. After all meshes were created, the Patran Equivalence tool was applied to remove any duplicate nodes and elements that may have been accidentally created during the process. All meshes for the King Air 350 were set to a 1 ft length, while those for the C-130 and Boeing 747-400 were created from 4 ft long meshes. These mesh sizes were chosen as to find a balance between resolution, computational power, and readability.

Next, boundary conditions and loads were applied to each model. The root of each wing was pinned and fully constrained as to represent the wing being attached to the aircraft. This pinning was applied to all nodes on the root including the base of each spar. Next the pressures calculated earlier for updraft and downdrafts, shown in Table 6, were applied to all the skin elements on the wings, and were assigned to different load cases such that only one was applied to the wing at any given time.

Properties were then assigned to the geometry. The skin for each wing was set to be twice the thickness of the aircraft skin, found in Table 1, as to approximate the thickness of the top and the bottom of each wing resisting the pressures applied, though the skin is only a minor contributor to overall structural integrity. Next each spar was created using the 1-D beam element properties creating I beams using the idealized I beam ratios from Figure 3 for the thickness of the wing at the relevant point along the wing as seen in Table 8. Each beam once generated was offset such that it is either sitting directly on the skin or slightly interlaced below the skin of the wing, care was taken to verify all spars in someone touched the aircraft skin. All elements were also assigned the Aluminum 6061-T6 material properties.

The models in Patran with geometry, meshes and load cases for the King Air 350, C-130, and Boeing 747-400 are shown in Figure 4.

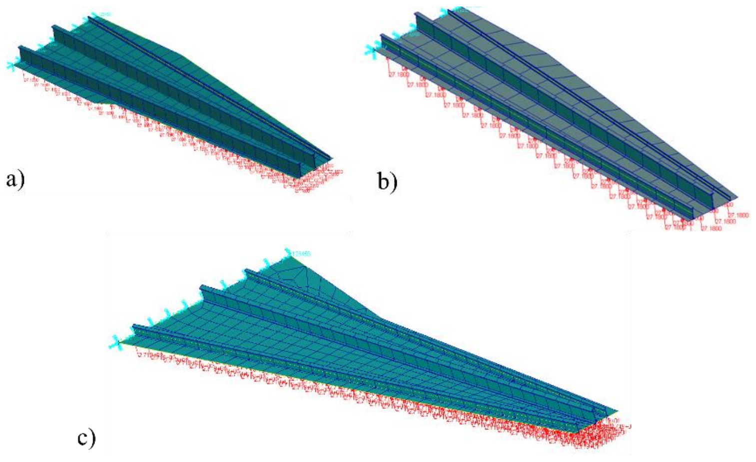

Figure 4. Geometry of wings under analysis with meshes, boundary conditions, and updraft pressure in Patran. a) King Air 350 wing b) C-130 wing c) Boeing 747-400 Wing.

Results

With geometries created and load cases applied, finite element analysis could begin. All models had an analysis deck generated and sent to Nastran to evaluate the results of the load applications on the wings. The resulting h5 analysis files were then input back into Patran to visualize the results of the loads on the beams. Each spar was then individually posted and had its maximum combined bar stress, max von Mises stress, and maximum displacement recorded the results for the updrafts and downdrafts are shown in Table 10 and Table 11 respectively.

Table 10. Wing spar stresses due to updraft

Aircraft	Spar	Max Combined Bar Stress [lbf/ft^2]	Max von Mises Stress [lbf/ft^2]	Max Displacement [ft]
King Air 350	Front	384,600	746,800	0.07327
	Middle	1,345,000	6,455,000	0.1384
	Rear	3,583,000	1,905,000	1.915
C-130	Front	550,100	449,900	0.4561
	Middle	1,535,000	1,815,000	0.7660
	Rear	3,709,000	1,231,000	2.085
Boeing 747-400	Front	1,286,000	4,118,000	1.124
	Middle	801,400	3,765,000	0.4855
	Rear	1,488,000	5,870,000	1.071

Table 11. Wing spar stresses due to downdraft

Aircraft	Spar	Max Combined Bar Stress [lbf/ft^2]	Max von Mises Stress [lbf/ft^2]	Max Displacement [ft]
King Air 350	Front	152,900	206,800	0.02029
	Middle	402,800	1,787,000	0.03833
	Rear	2,783,000	527,500	0.5302
C-130	Front	164,200	124,600	0.1263
	Middle	698,700	502,600	0.2121
	Rear	2,830,000	340,800	0.5773
Boeing 747-400	Front	433,700	1,140,000	0.3113
	Middle	217,200	1,042,000	0.1344
	Rear	529,700	1,625,000	0.2965

When looking at the data as a whole there are some general trends that can be observed. First, that in all cases rear spar max combined bar stress is larger than that experienced by any other spar comparing the same metric. This can be explained on the basis that the rear spar is the smallest as the rear of the wing is less thick than the front, and sometimes due to wing geometry the rear spar has more skin area around it than the other spars will have. Next, it can be observed that when looking at von Mises stress that in the case of updrafts the middle spar experiences the most stress in the King Air 350 and C-130 while in the 747-400 it occurs in the rear spar. This trend makes sense as both King Air 350 and C-130 wings are not swept and are generally rectangular resulting in the middle spar having the most skin area around it to lift and cause stress. Finally, when looking at displacement the King Air 350 and C-130 both have their maximum displacements occurring on the rear spar while the Boeing 747-400 has it occur on the front spar with the rear spar closely matching.

The primary data of focus is in comparing the Max von Mises stress to the tensile yield strength of Aluminum 6061-T6 to ascertain if the materials will begin to yield. As seen in Table 9, Aluminum 6061-T6's yield strength is 5,760,000 lbf/ft^2, which is less than some of the stresses experienced by some spars. First, all spars receive less than yield stress during the downdraft load case with the highest one, the middle spar on the King Air 350, only being 30% of the yield stress. The updraft case, however, is quite different.

When comparing von Mises stress to yield stress for the updraft case, two spars experience stress higher than the yield strength, the King Air 350's middle spar and Boeing 747-400 rear spar both experience stresses exceeding this limit. This would lead to these spars beginning to yield and possibly permanently deform leading to the aircraft's structural integrity being at risk.

Conclusion

Updraft and downdrafts from wildfires are an increasing threat to unsuspecting aircraft, as airplanes are suddenly buffeted by their forces. This analysis attempting to characterize these forces and the stresses they apply to aircraft of varying sizes as to attempt to identify any general problem areas. In this pursuit finite element models were developed in Patran to study both the updraft and downdraft effects on wings. Using prior data, the updraft was found to travel at 130.4 mph (58.3 m/s) and the downdraft travel at 65.5 mph (29.3 m/s) (Rodriguez, Lareau, Kingsmill, and Clements 2020). Next, preliminary analysis was conducted to determine ambient air conditions at the altitude where super-heated air readings were recorded. These values of pressure at altitude were then used to derive the density of the super-heated air after determining its flow speed was low enough such that the incompressible assumption could be applied. Next, drag per unit area was calculated using the assumption that the wings were perpendicular to the flow of the updrafts and downdrafts allowing them to be approximated as flat plates perpendicular to the air flow. From this it was found that the updrafts imparted a 27.189 lbf/ft^2 pressure while the downdrafts imparted a 7.428 lbf/ft^2 pressure on wings. With these pressure values the areas of each wing was applied to determine the total force applied to each aircraft under updraft and down draft conditions.

From here finite element analysis was conducted on wings from the King Air 350, C-130, and Boeing 747-400 as to model aircraft of varying sizes. These wings were measured in Solid Edge before being recreated in Pastran. Here their geometry was defined, and a 1 ft mesh was applied to the King Air 350 model while 4ft meshes were applied to the C-130 and Boeing 747-400 wing models. Material (Aluminum 6061-T1) and property values for wing skin and spar heights were applied next. Through analysis was then conducted in Patran and Nastran. It was found that the middle wing spar on the King Air 350 and the rear spar of the Boeing 747-400 experienced stresses exceeding the yield strength of the chosen aluminum, which will result in material yielding. This can pose a risk to the structural integrity of the wing and potentially endangering the integrity of the aircraft as a whole. It must be noted that this is a simplified analysis that has streamlined many portions of the structure of an aircraft wing, so further study should be conducted with more through models that include the impact of other aircraft structural components such as ribs and use spar geometry based on exact sizing of real-world aircraft to truly understand the risks that may be involved to aircraft safety for each air frame.

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